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NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

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COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Flue Gas Desulfurization By Scrubbing With Dilute Sulfuric Acid

Appendix 95-H

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Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations - Flue Gas Desulfurization By Scrubbing With Dilute Sulfuric Acid

APPENDIX 95-H

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SUMMARY

The Chiyoda Thoroughbred 101 (CT-101) process, the only flue gas desulfurization (FGD) system on the market using sulfuric acid scrubbing, is gaining popularity. Fourteen systems are in operation in Japan, ranging in capacity from 30 MW to 350 MW.

The CT-101 process removes SO_2 from flue gas by use of a 2 to 5 percent sulfuric acid solution containing ferric ion catalyst. The resulting sulfuric acid reacts with limestone ($CaCO_3$) to produce gypsum ($CaSO_4 \cdot 2H_2O$).

In Japan, CT-101 has been applied to the treatment of Claus sulfur plant tail gas, industrial incinerator flue gas, and oil-fired boiler flue gases. A demonstration system was built in the United States at the Scholz plant of Gulf Power Company in Sneads, Florida, to test the CT-101 process on a coal-fired boiler. Test results indicated that the chloride and the common metal ion concentrations were below design levels. Overall performance was satisfactory, achieving over 85 percent SO_2 removal efficiency. The test

demonstrated that a properly designed and operated CT-101 system should be superior to that of direct lime and limestone systems.

The dilute acid process is applicable to areas where gypsum can be marketed nearby, land costs are high, solid waste regulations are strict, or NO_x control is required or regulations are imminent. Alternatively, the gypsum can be used as landfill in areas where land is readily available. The system is well developed for small or large boilers and for use where particulate content of flue gas entering the system is very low. It is currently being tested on all types of coal boilers. Water and lime/limestone are required raw materials, however, and the system must be located near sources of both.

The CT-101 process is still relatively untried on large-scale, coal-fired boilers and the marketability of the by-product gypsum in the United States is unknown. It has numerous inherent advantages and several distinct disadvantages compared with conventional, first-generation FGD scrubbing processes now available to the U.S. utility industry. These are summarized as follows:

Advantages:

1. The process is simple and the operation relatively easy.
2. SO_2 removal efficiency is normally over 90 percent.

3. The catalyst is cheap, readily available, and highly resistant to poisoning by organic contaminants in the flue gas. It also acts as a corrosion inhibitor.

4. Scaling and plugging are not problems.

5. Front-end subsystem (absorption and oxidation) can function independently of the back-end subsystem (crystallization and gypsum production) for short periods (1 to 2 days) without a corresponding decrease in operating efficiency. Ability to stop the gypsum-producing system while absorption continues can sometimes preclude total system shutdown.

6. The gypsum produced is of high quality and easily handled.

7. Process reliability is relatively high.

8. The process has significant capability for NO_x removal.

Disadvantages:

1. High liquid-to-gas (L/G) ratios are required for high SO_2 removal efficiency.

2. Relatively large pumps and absorption and oxidation modules are required to maintain the high L/G's.

3. On a coal-fired boiler, virtually all fly ash must be removed (down to 73 g/Nm^3) upstream of the system. Therefore, a highly efficient ESP or a venturi prescrubber are required for particulate removal.

4. Special corrosion-resistant metals are required because sulfuric acid solutions are used.

5. A centrifuge requires frequent maintenance.

6. Critical water concentration in the gypsum product is 15 to 18 percent by weight. If the concentration is higher, the product is not of commercial grade and cannot be used for wallboard production.

7. On a coal-fired boiler, a potentially large system blowdown must be treated before being disposed of because of its high chloride and solids concentrations.

8. The process is relatively expensive compared with lime/limestone gypsum processes.

1.0 BACKGROUND AND INTRODUCTION

This report is one of a series on the status of FGD in the NATO Countries and Japan. The United States, the Federal Republic of Germany, and Norway have acted as lead countries in gathering information for the preparation of the reports.

In sulfuric acid scrubbing processes, sulfuric acid solutions are used in a scrubber to absorb SO_2 from the flue gas.

The literature indicates that two different methods are used to apply the sulfuric acid solution. One involves powerful oxidants such as H_2O_2 (Tysul process) and peroxymonosulfuric acid (Peracidox process), and the other involves catalysts such as activated carbon, manganese ion, or ferric ion.

As early as 1956, the Tennessee Valley Authority (TVA) added a small amount of ozone to the stack gas and scrubbed the gas with a dilute sulfuric acid containing manganese ion catalyst. The maximum acid strength attainable was about 40 percent, and the catalyst was easily poisoned by the organic contaminants in the flue gas.

In Japan, Chiyoda Chemical Engineering and Construction Company, Ltd. conducted a series of experiments to eliminate the deficiencies of the manganese catalyst. The results of these tests led to the patenting of the CT-101 process, which uses ferric ion as a catalyst. After bench-scale tests between 1970 and 1971, a three-month pilot plant operation was carried out successfully.

Since its introduction in October 1971, the CT-101 process has been installed in 14 oil-fired plants in Japan (representing over 1700 MW) and all are operating smoothly. The Japanese have no coal-fired plant applications of the CT-101 process because of their lack of coal-fired boilers.

The CT-101 process has recently been tested in the United States on a coal-fired boiler. The demonstration system was constructed at the Scholz plant of the Gulf Power Company in Sneads, Florida.

2.0 GENERAL PROCESS DESCRIPTION

The CT-101 process uses dilute sulfuric acid solution to absorb the SO_2 in the flue gas. The absorbed SO_2 gas is oxidized with air and forms additional sulfuric acid. The acid thus produced is reacted with limestone ($CaCO_3$) to produce gypsum ($CaSO_4 \cdot 2H_2O$) as a salable by-product. Ferric ion was chosen as a catalyst for the oxidation step because it is harmless, available, and resistant to poisoning by contaminants. Figure 1 presents a simplified hypothetical flow diagram and material balance of a 500-MW, coal-fired boiler with a dilute sulfuric acid desulfurization system. Data were obtained from the publications and prorated for a 500-MW capacity.

2.1 PROCESS CHEMISTRY

The CT-101 process includes three major process areas: absorption, oxidation, and crystallization. The overall reactions that take place in the absorber are:

$$SO_2(g) + H_2O \rightarrow H_2SO_3 \qquad (1)$$

At the flue gas-scrubbing solution interface in the absorber, the SO_3 anion forms in the following manner:

$$H_2SO_3 \rightarrow H^+ + HSO_3^- \qquad (2)$$

$$\text{and } HSO_3^- \rightarrow H^+ + SO_3^{=}$$

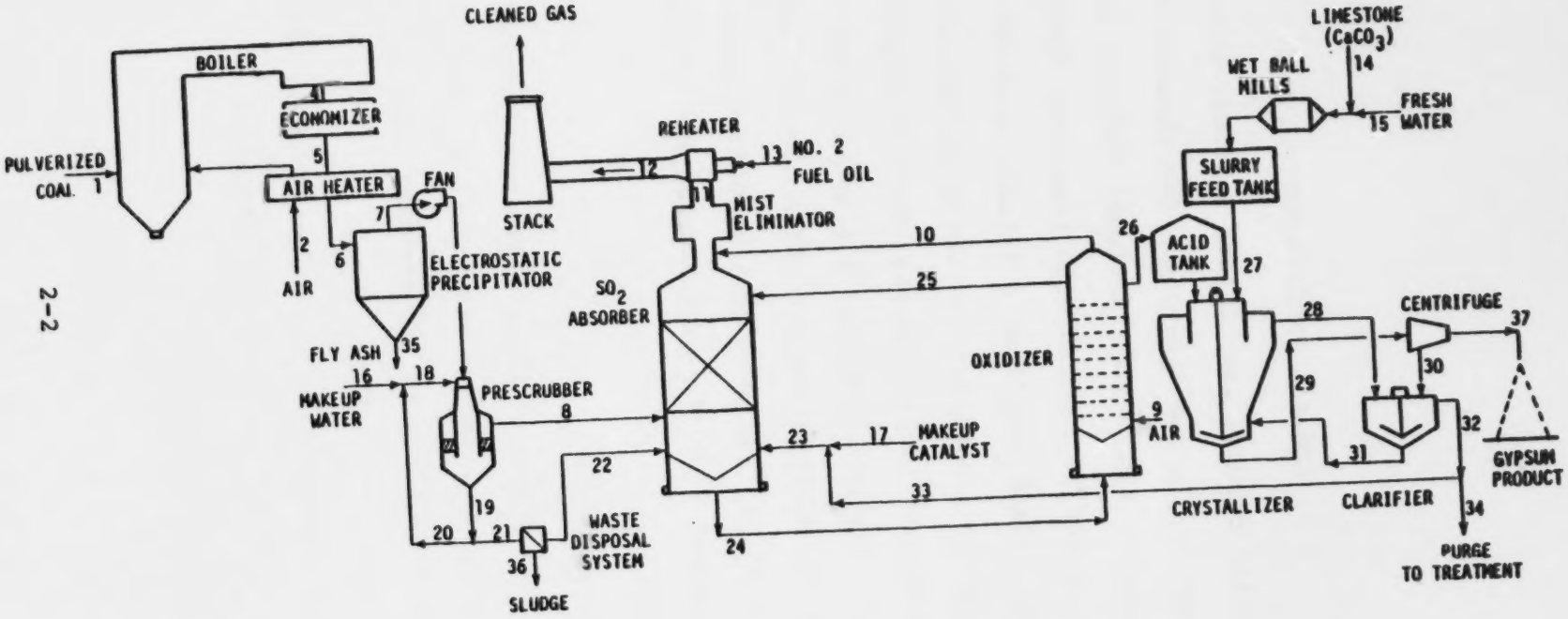

Figure 1. Example process flow diagram and material balance for a 500-MW, coal-fired boiler and dilute sulfuric acid desulfurization process.

(See notes at end of figure.) (continued)

Stream No.	1	2	3	4	5	6	7	8	9	10
Description	Coal to boiler	Air to air heater	Air to boiler	Gas to economizer	Gas to air heater	Gas to ESP	Gas to prescrubber	Gas to SO_2 absorber	Air to oxidizer	Spent air
Rate, 1000 kg/h	170	2049	1848	1998	1998	2199	2186.8	2282.4	52	53.83
Nm^3/s		464	419	445	445	490	490	524	11.3	12.3
m^3/s liquid										
Particulates, kg/h				15,300	15,300	15,300	3060	1530		
Temperature, °C		43.3	279	477	374	154	154	53	25	53
Specific gravity										
Viscosity, Pascal-seconds										
Undissolved solids, %										
pH										
Sulfur as SO_2 kg/h	11,900			11,900	11,900	11,900	11,900	10,710	-0-	-0-

Stream No.	11	12	13	14	15	16	17	18	19
Description	Gas to reheater	Gas to stack	No. 2 fuel oil for reheat	Limestone feed to ball mills	Water to ball mills	Makeup water	Makeup catalyst	Prescrubber solution	Spent solution
Rate, 1000 kg/h	2324.2		2.85	16.8	67.2	126.2	2.5	9084.6	8989
Nm^3/s	535								
m^3/s liquid			0.00088		0.0187	0.035		2.45	2.424
Particulates, kg/h	1530	1530						454,230	449,450
Temperature, °C	53	93							
Specific gravity			0.895		1.0	1.0		1.03	1.03
Viscosity, Pascal-seconds									
Undissolved solids, %					-0-	-0-		5	5
pH									
Sulfur as SO_2 kg/h	1145	1190	45.54					353,290	239,600

Figure 1 (continued).

Stream No.	20	21	22	23	24	25	26	27	28
Description	Recycled solution	Purge disposal system	Recovered water	Recycled acid	Spent acid to oxidizer	Acid to SO_2 absorber	Acid to acid tank	Limestone slurry to crystallizer	Crystallizer overflow
Rate, 1000 kg/h	8958.4	30.6	27.2	1474.6	95600	94086	1512	84	4551
Nm^3/s									
m^3/s liquid	2.416	0.0083	0.0756	0.41	26.556	26.135	0.42	0.0212	1.193
Particulates, kg/h	447,900	1530	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Temperature, °C					53	53	53		48
Specific gravity	1.03	1.03	1.0	1.0	1.0	1.0	1.0	1.1	1.06
Viscosity, Pascal-seconds									
Undissolved solids, %	5	5	-0-	-0-	-0-	-0-	-9-	20	10
pH									
Sulfur as SO_2 kg/h	348,400	1190	-0-						

Stream No.	29	30	31	32	33	34	35	36	37
Description	Crystallizer underflow	Centrate to clarifier	Clarifier underflow	Clarifier overflow	Recycled acid to absorber	Purge to treatment	Fly ash disposal	Sludge disposal	Gypsum product
Rate, 1000 kg/h	102.4	70.4	3057	1564	1472.1	91.9	12.24	3.4	32
Nm^3/s									
m^3/s liquid	0.0237	0.0190	0.779	0.434	0.409	0.0255			
Particulates, kg/h	-0-	-0-	-0-	-0-			12,240	1530	
Temperature, °C	48								
Specific gravity	1.2	1.03	1.09		1.0	1.0			
Viscosity, Pascal-seconds									
Undissolved solids, %	30	5	15	-0-	-0-	-0-		80	85
pH									
Sulfur as SO_2 kg/h								1190	9565

Calculations based on:

1. 90% particulate removal - overall.
2. Prescrubber - 50% efficiency.
3. 90% SO_2 removal - overall.
4. No. 2 fuel oil contains 0.8% sulfur.
5. Air - 5 times stoichiometric ratio.
6. Scrubbing solution is 2% H_2SO_4.
7. Acid is diluted to 1% in the crystallizer.
8. Purge stream (No. 34) has 200 ppm Cl-.
9. Limestone utilization is 98%. S.R. = 1.1
10. 2000 ppm catalyst in recirculation stream (No. 33).
11. Makeup catalyst is 10% solution.
12. Prescruber L/G = 5 liter/m^3.
13. Absorber L/G - 50 liter/m^3.

Figure 1 (continued).

The catalytic oxidation reaction proceeds as follows:

$$SO_2\ (dis) + 2H_2O + Fe_2(SO_4)_3 \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (3)$$

$$SO_2\ (dis) + O_2\ (dis) + 2FeSO_4 \rightarrow Fe_2(SO_4)_3 \quad (4)$$

and,

$$2H^+ + SO_3^{=} + H_2O + Fe_2(SO_4)_3 \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (5)$$

In this stage, oxidation is aided by dissolved catalyst of ferric sulfate, $Fe_2(SO_4)_3$.

The sulfuric acid is sent to the crystallizer and neutralized with limestone to a concentration of 1 percent H_2SO_4, which generates a gypsum by-product in the following manner:

$$H_2SO_4 + H_2O + CaCO_3 \rightarrow CaSO_4 \cdot 2H_2O \downarrow + CO_2 \uparrow \quad (6)$$

As a result of heat loss, the operating temperature is approximately 5°C lower than in the absorption and oxidation sections.

According to the stoichiometry, 1 mole of limestone is required to remove one mole of SO_2. Assuming 10 percent excess,* actual limestone required is

$$\frac{100}{64} \times 1.1 = 1.72 \text{ kg/kg of } SO_2$$

and the gypsum produced is

$$\frac{172}{64} + \frac{100}{64} \times (1.1 - 1.0) = 2.84 \text{ kg/kg of } SO_2.$$

The gypsum by-product contains about 10 percent free water.

---

* The experience at Scholz indicated the stoichiometric ratio of approximately 1.05, since limestone would be required to neutralize the sulfate ion introduced with the catalyst makeup. For this example, however, the ratio of 1.1 was used for convenience.

2.2 DESCRIPTION OF EQUIPMENT COMPONENTS

The CT-101 FGD system is a second-generation scrubbing process involving five basic process units: a prescrubber, an SO_2 absorber, an oxidizer, a crystallizer, and a centrifuge for dewatering the gypsum by-product.

2.2.1 Prescrubber

The flue gas from the ESP is treated initially in a prescrubber, which cools the incoming flue gas to 50°C and removes dust, fly ash, and chlorides. The prescrubber consists of a fixed-throat venturi scrubber constructed of type 316L stainless steel and lined with fiberglass reinforced polyester (FRP). The settled solids in the prescrubber recycle stream are discharged to control the solids concentrations. The prescrubber has achieved particulate removal efficiencies up to 50 percent on oil-fired systems.

2.2.2 SO_2 Absorber

The SO_2 absorber is the primary SO_2 removal unit in the system. The SO_2 is removed from the cooled, prescrubbed flue gas by means of countercurrent scrubbing with weak sulfuric acid in a fixed-bed absorber.

The scrubber must be constructed of materials resistant to corrosion, erosion, and scaling. Most scrubber bodies

are constructed of mild steel and lined with an acid-resistant coating such as FRP, rubber, or glass flake. Scrubber internals may be made of a variety of materials such as stainless steel, which has a tendency to pit; high nickel alloys, which are expensive; or FRP, which is fragile.

The absorption tower of the CT-101 process is a packed column constructed of 316L stainless steel and filled with 7.5-cm Tellerette packing material.

2.2.3 Demister

A demister is necessary to remove entrained water from the scrubber outlet gas so that corroding or scaling of downstream equipment can be prevented. Additional energy in the reheater also is required to evaporate the droplets. The water droplets are large enough to be removed with a simple change in flue gas direction. The CT-101 process utilizes an impingement-type Chevron mist eliminator with waved polypropylene plates. The efficiency of this unit is about 95 percent.

2.2.4 Reheater

Reheating of stack gas is generally necessary to increase its buoyancy and dispersion and to prevent corrosion of equipment. Reheating can be accomplished by installing a gas or oil burner that exhausts directly into the

stack, installing steam coils to heat the flue gas, injecting preheated air into the stack, or injecting by-passed, hot flue gas into the stack. In the present CT-101 process design, hot gas from fuel oil combustion in a horizontal refractory furnace is exhausted into the stack.

2.2.5 Oxidizer

The oxidizer, a bubble column made of several sheets of polypropylene net or type 316 L stainless steel perforated trays, is positioned downstream from the absorber. Spent dilute sulfuric acid is pumped from the absorber to the bottom of the oxidizer, where air is injected.

The absorbent, at a temperature of about 60°C, flows upward through the oxidizer concurrently with air.

Aided by a soluble catalyst of ferric sulfate, the SO_2 dissolved in the absorbant is completely oxidized by the injected air and forms sulfuric acid. The air requirement is generally five times that required to oxidize all the SO_2. Most of the sulfuric acid (saturated with oxygen) is returned to the absorber at a temperature of 53°C.

The absorption towers of commercial plants are provided with rubber or FRP linings for corrosion protection. Ferric sulfate catalyst also works as a corrosion inhibitor.

A high L/G ratio is required to attain high SO_2 recovery. Large pumps and a fairly large absorber and oxidizer

also are required. Typical absorber tower sizes are presented in Table 1.

Table 1. ABSORBER TOWER SIZES REQUIRED FOR THE CHIYODA PROCESS

(meters except as noted)

Capacity, Nm^3/h	Absorber		Oxidizer	
	Diameter	Height	Diameter	Height
200,000	9.9	16.5	4.5	20.9
400,000	16.5	16.5	7.0	20.9

2.2.6 Crystallizer

A special type of crystallizer has been developed to obtain good crystalline gypsum suitable for dehydration by conventional centrifuges. This is an inner circulating type crystallizer built of 316L stainless steel. The acid is neutralized with powdered limestone (74 percent under 200 mesh) to a concentration of 0.7 to 1 percent. Tables 2 and 3 show the quality of the limestone and the gypsum at one operating plant.

2.2.7 Centrifuge

The gypsum-suspended liquor is then sent to a centrifuge, where gypsum is separated from the mother liquor.

At the Scholz facility, the unbalancing of a screw decanter (solid bowl-type) centrifuge was a continuous

Table 2. LIMESTONE REAGENT QUALITY

Property	Value
Specific gravity	2.70
Particle size	
100-mesh pass, %	99.43
200-mesh pass, %	95.15
325-mesh pass, %	85.72
Chemical composition, wt %	
SiO_2	2.5
Al_2O_3	0.4
Fe_2O_3	0.2
CaO	53.8
MgO	0.5
as $CaCO_3$	96.2
Free water, wt %	0.2

Table 3. GYPSUM QUALITY

Property	Value
Specific gravity	2.32
Stokes diameter, 10^{-6}m	91
Chemical composition, wt %	
CaO	31.5
SO_3	44.75
CO_2	0.11
pH	6.4
Free water, wt %	6.1

problem. This was primarily caused by excessive nonuniform rate of wear on the screw. Chiyoda's experience in Japan has generally shown basket-type centrifuges to be superior to the solid-bowl machines used at Scholz.

The following are some centrifuge design considerations:

(1) Moving parts should be given hard surfacing treatment to avoid/eliminate the wear problems.

(2) Wash-out connections (that are capable of thoroughly washing centrifuge internals) should be installed.

(3) The system should be designed to handle a wide range of input solids concentrations and viscosities while providing good separation.

Table 4 summarizes pertinent information concerning the CT-101 process equipment and materials of construction.

2.3 OPERATING PARAMETERS

2.3.1 Chemical Parameters

The activity of the ferric sulfate catalyst at room temperature is low compared with that of the manganese ion catalyst. At temperatures between 50 and 60°C, however, Fe^{+++} is active enough to achieve greater than 80 percent SO_2 removal. Oxidation ratio generally increases as the temperature increases. When the temperature rises above 95°C, however, the solubility of oxygen is reduced to a point where it affects the oxidation rate. One advantage of the ferric ion catalyst is that it is not affected by the contaminants in the flue gas.

Table 4. MAJOR EQUIPMENT IN THE TOYAMA-SHINKO PLANT
(Equivalent to 250-MW utility boiler)

Item	Quantity	Specifications and material of construction
Prescrubber	2	Venturi type: titanium and 316L stainless steel.
Absorber-oxidizer	1	Cylindrical type: 21 m D. x 28 m H., 316L stainless steel. Absorption section: packed column; 21/9.4 m D. x 9.1 m H., 316L stainless steel. Oxidation section: perforated trays column: 9.4 m D. x 9.1 m; 316L stainless steel.
Crystallizer	1	Cylindrical (Chiyoda Inner-Circulation Type): 500 m^3, 22kVA; 316L stainless steel.
Clarifier	1	Cylindrical type: 300 m^3; rubber lining.
Limestone storage	1	Vertical cylindrical type: 8.6 m D. x 20.8 m H., 500 m^3 carbon steel.
Flue-gas fan	1	Turbo-fan; 763,000 Nm^3/h x 71 cm H_2O head, 2,500 kVA; carbon steel.
Absorbent-recycle pump	3[a]	Centrifugal: 11,200 kiloliter/h x 20 m head; 800 kVA; rubber lining and 316L stainless steel.
Air blower	2	Two stages, turbo-fan; 7460 Nm^3/h x 1.9 ATM. gauge, 300 kVA; carbon steel.
Centrifuge	3	Basket-type, fully automatic: 1.7 ton/h of cake each, 37 kVA; 316L stainless steel.
Reheater furnace	1	Horizontal type: 3.6 m D. x 7.3 m length; refractory.
Mist eliminator	1	Impingement type; two stages; rubber lining and polypropylene.

[a] Two plus one spare.

2.3.2 Physical Parameters

Under certain conditions, the sulfite, sulfate, bisulfite, and bisulfate may react with various metallic contaminants in the flue gas and be converted to insoluble sulfate compounds, causing solids build-up and plugging in the absorber. The absorption section of the CT-101 process, therefore, cannot tolerate certain metallic contaminants (e.g., V, Al, Mg, Mn, Na, Ca) in excess concentration. When this process is used to remove SO_2 from coal-fired flue gas, the collection efficiency of the upstream particulate removal devices must approach 100 percent.

To attain high SO_2-removal efficiency, an L/G ratio of 30 to 40 liter/Nm^3 is required. The gas velocity in the absorber is about 0.6 m/s, and the air required for oxidation is about five times the stoichiometric requirement.

Although decreasing the sulfuric acid concentration in the absorbant reduces energy consumption by decreasing the L/G ratio, it raises the construction cost of the crystallization section. On the other hand, increasing the sulfuric acid concentration in the absorbent lowers the construction cost but increases the L/G ratio and, thus, the electricity consumption.

The concentration of sulfuric acid in the returned absorbant is considerably lower than it is in the absorption

and oxidation section, where it ranges from 2 to 5 weight percent. Therefore, even if the returned absorbent contains a considerable amount of calcium sulfate (from 0.01 to 0.05 wt. %), the solids are dissolved in the sulfuric acid concentrations and no plugging occurs from the crystallization of calcium sulfate.

Because the chloride contained in fresh water and fuel accumulates in the absorbent and causes pitting in the construction materials, an allowable limit of 200 ppm chloride was adopted for the absorbant to protect the exposed 316L stainless steel material. One study indicated, however, that no significant corrosion occurred in 316L stainless steel up to about 400 ppm chloride in the liquor because of the corrosion-inhibiting effects of ferric ion from the catalyst and of nitrate ion (from NO_x in the flue gas). Wastewater discharged from the full-scale Chiyoda process is neutralized to a quality that satisfies the local control standards.*

Flue gas is reheated sufficiently (17° to 44°C) to prevent condensation of the moisture in the gas. Depending on the method, reheating requires an energy expenditure of approximately 1100 J/kg flue gas/°C reheat.

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* Because of the small size of the process at Scholz, Chiyoda decided not to install a waste-neutralization, catalyst-recovery system.

3.0 CURRENT STATUS, ASSESSMENT, AND PLANS

Fourteen commercial plants in Japan (with capacities up to 350 MW) use the CT-101 process to control SO_2 emissions. The first of the systems was put into operation in November 1972 and the most recent one in April 1976.

Many details of process design and chemistry have been worked out under operating conditions. After slight modifications, all the units are running satisfactorily with SO_2 removal efficiencies of more than 90 percent.

The gypsum separated from the centrifuge is easily handled in bulk because it is in a dry powder state with a free water content of less than 10 percent. The gypsum is of high quality and is marketed for the manufacture of wallboard and for use as a cement retarder.

The Scholz plant of Gulf Power Company in Sneads, Florida, recently terminated its performance test of the CT-101 process in the removal of SO_2 from flue gas generated by a coal-fired boiler. Test results indicated that particulate removal efficiency in the prescrubber ranged from 33 to 96 percent under low particulate loading conditions and was more than 99 percent under high particulate loading conditions.

Average SO_2 removal efficiency was about 85 percent. The test demonstrated that SO_2 removals in excess of 90 to 95 percent could easily be achieved with more energy input.

Under the best of circumstances, some chlorides will pass through the prescrubber and be captured in the absorber, causing the chloride concentration in the absorption/ crystallization sections to build to a level sufficient to maintain a material balance. If this level is above about 400 ppm, it is necessary to institute a liquid purge from the system for chloride control. At the Scholz plant, the process requirements for water input into the absorption/ crystallization section were in excess of the water which left the system associated with gypsum cake. (This was due principally to the excessive flushing water requirements of the mechanical seals used on the oxidizer feed pumps.) Therefore, a liquid blowdown was necessary to maintain the water balance in the absorption/crystallization portion in addition to any chloride purge.

No common metal ions were found in the process liquor in concentrations in excess of 30 ppm; this was significantly below the minimum levels previously found to affect process operation. These tests also confirmed the viability of system operation without a mist eliminator wash and without any mist eliminator scaling.

The overall performance of Scholz proved that a properly designed and operated CT-101 system should be superior to direct lime and limestone systems because:

1. The system is highly resistant to upset;
2. Slurry handling in the absorption section is minimal;
3. Close control of acid concentration is not necessary to control scaling.

The dilute acid process is well suited to siting in an industrial area, where the gypsum product or dilute acid can find more uses. If the product is sold, no large disposal area is necessary. The FGD system requires about as much space as a boiler. This process is especially good if gypsum is in short supply and must be imported. Beyond that, new uses are being found for gypsum every day. The biggest disadvantage of the process is its high capital cost, due to the highly corrosive nature of dilute sulfuric acid.

Table 5 summarizes the status of the CT-101 process, and Table 6 presents significant characteristics of each surveyed facility. The questionnaires in the Appendix contain more detailed information.

Table 5. SUMMARY OF STATUS OF SURVEYED FGD SYSTEMS

All Systems	
Projected number of systems in operation by Dec. 77	14
Total number of systems built	15
Total number of systems surveyed	2
Year first placed in commercial service	1972
Number of utility systems using process	4
Total MW of utility systems	1100
Number of industrial combustion systems	10
Surveyed Systems	
Average SO_2 removal efficiencies, %	over 90
Range of fly ash removal efficiency, %	N.A.[a]
Range of average availability factors[b], %	94-100

[a] N.A. Not available.

[b] See Appendix.

Table 6. STATUS OF SURVEYED FGD INSTALLATIONS, CHIYODA THOROUGHBRED 101 PROCESS

Name of plant	Location	Size, MW	Fuel type	Characteristics		Flue gas treated		Year FGD systems started	SO_2 removal efficiency, %	Disposition of end products	Energy required % total input	Avg. % availability
				%S,	Heat value, 10^6 J/kg	Nm^3/s	% of total					
Scholz	Snead, FL	21	Coal	1.7-2.5	28.4	25	100	1975	85	Gypsum	- [a]	97 (9/1975 - 12/1975)
Fukui	Fukui Japan	350	Oil	2.5-3.0	43.7	297	100	1975	95.6	Gypsum	3.5 [b]	100

[a] Energy data not available.

[b] In addition 4.2 percent reheat energy required.

4.0 RECENT TECHNOLOGICAL DEVELOPMENTS AND SOLUTIONS TO PROBLEMS

4.1 RECENT TECHNOLOGICAL DEVELOPMENTS

Technological developments have occurred in both equipment and process design.

At the Toyama-Shinko plant, the absorber and oxidizer were combined in one cylindrical column 21 m in diameter x 28 m in height (Figure 2). The column consists of two concentric shells with a center area for oxidation and an annulus for absorption. This configuration increases the mechanical strength of the internal supports and promotes liquid distribution at the top of the column. Stainless steel, FRP, rubber lining, etc., can be used as construction materials. This type of reactor saves both space and capital expenditure.

Using the established CT-101 FGD process as a basis, Chiyoda Engineering Company has developed the Chiyoda Thoroughbred 102 (CT-102) for simultaneous removal of SO_2 and NO_x. Pilot plant tests were carried out in a unit with a capacity of 1000 Nm^3/h, and patent application was filed in 1973. The main modification involves mixing dilute ozone

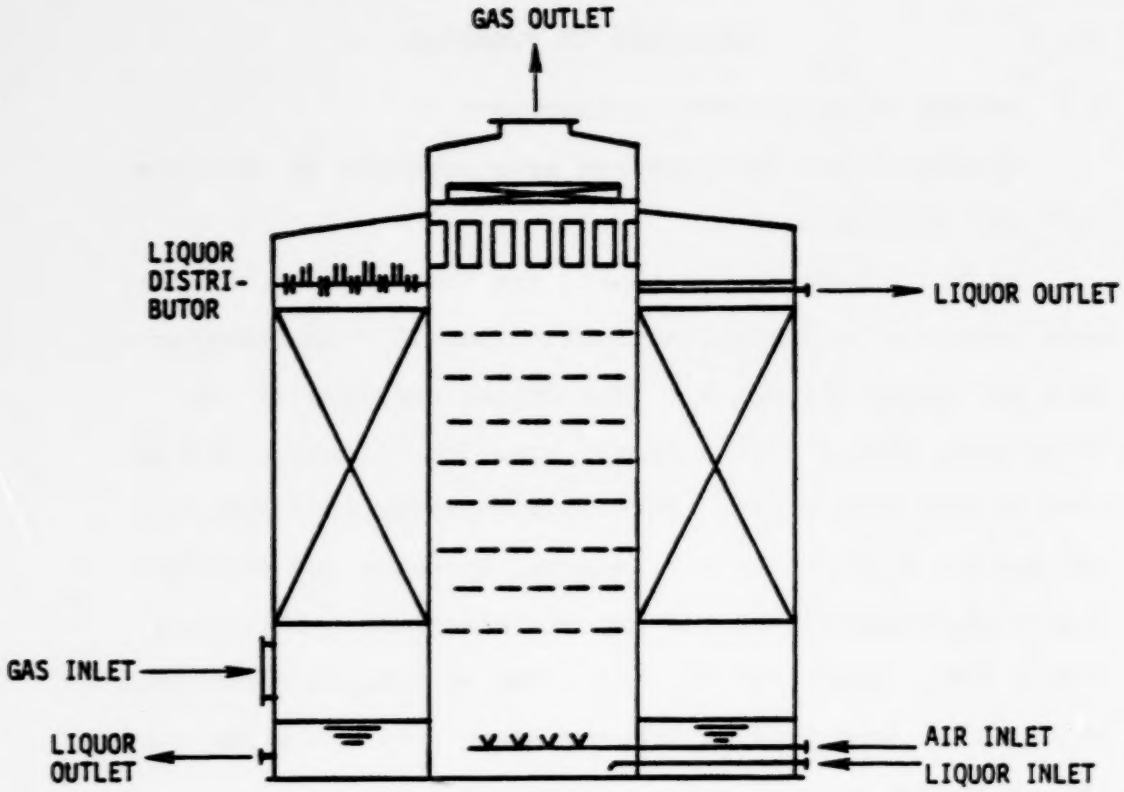

Figure 2. Double-cylinder type absorber-oxidizer.

with the flue gas from the prescrubber. Most of the NO_x is oxidized and then removed simultaneously with SO_2 in the absorber. Part of the NO_x becomes nitric acid and the balance is discharged as N_2 and N_2O.

A portion of the absorbant is continuously withdrawn from the recirculation system to maintain a constant nitric acid concentration and to limit the accumulation of chlorides and soluble salts. The removal rate of NO_x will range from 60 to 90 percent, depending on the amount of ozone added.

Chiyoda claims that the desulfurization rate is higher with simultaneous removal of SO_2 and NO_x than with SO_2 removal only. The amount of ozone added seems to be a critical operating factor.

4.2 SOLUTIONS TO PROBLEM AREAS

After the introduction of the CT-101 process, four systems were designed and constructed almost simultaneously. Some of the problems encountered and the methods used to solve them are listed below:

1) Velocity in horizontal piping was too slow, causing gypsum deposits. Piping was inclined and smaller sized pipes were adopted.

2) Gypsum erroded rubber-lined globe valves. Stainless steel valves of a different style were installed.

3) Air spargers for oxidation became plugged by gypsum crystals. A clarifier was installed to minimize carry-over of gypsum crystals in recycling absorbant from the centrifuge. Sparger holes were enlarged, and air is cooled before it enters the oxidizer.

4) More than 15 percent of the by-product gypsum was free water, which caused difficulty during bulk handling with dump trucks and decreased the capacity of the wallboard manufacturer's dryer. The crystallizers were redesigned with longer holding time to obtain a larger crystal size that could be more easily dewatered in the centrifuge.

5) Pitting corrosion on some parts of stainless steel plates was caused by accumulated chloride ions in the absorbant when burning low-grade oil. The chloride content was reduced to 200 ppm by adjusting the purge rate.

The problems encountered at the Scholz demonstration facility were mostly mechanical and operational. The first few months were characterized by the usual small start-up problems and the resulting outages. Many of these early problems resulted from the work crew's attempt to become familiar with the mechanics of this process and two other FGD systems simultaneously.

Centrifuge vibration caused a 6-week outage in August and September. This problem, which resulted primarily from nonuniform wear of the Stellite No. 1 hard facing on the screw conveyors, was not entirely resolved during the test program.

Other miscellaneous problems included several minor pump malfunctions, jamming of the limestone feeder, FRP leakage, and some instrumentation difficulties, especially with slurry analyzers and level transmitters.

5.0 COST

Cost data on this process are very limited. Some data were obtained from the publications listed in Section 6 and some were estimated (as indicated in Table 7). Escalation to January 1976 dollars was accomplished by using the Chemical Engineering Plant Cost Index (1957 - 59 = 100, Jan. 1976 = 187.1).

Capital cost of the Toyama-Shinko plant (250-MW FGD capacity) was approximately $7.33 million or about $30/kW at the time of construction (between December 1971 and April 1973). The absorption and oxidation section accounted for 65 percent of this figure and the crystallization section for 35 percent. Two operators are required per shift, four shifts a day, and the average operating cost is 2.6 mills/kWh.

The total installed capital cost of the Scholz demonstration unit (23 MW) is reported to be $5.4 million or about $235/kW. In 1975, Chiyoda International Corporation estimated that the CT-101 unit would cost from $80 to $100/kW for a 250-MW power plant in the United States.

Table 7. COST DATA OF INDIVIDUAL INSTALLATIONS FOR THE DILUTE ACID PROCESS

Company Name Plant Name Location	Hokuriku Elec. Fukui Fukui Japan	Gulf Power Scholz Sneads, FL USA
1. Reported capital costs, $		5,405,000
Year	1974	1975
Cost inflated to 1976		5,566,000
$/kW		242
2. Reported annual costs, $		
Total fixed costs		1,129,000[a]
Fixed charge factor, %		20.28
Total variable costs[b]		1,101,000
3. Boiler operating hours	7290	
Capacity factor	0.63	
Generated MWh		
4. Reported cost per kWh, mills/kWh		18.45[a]
Fixed cost		
Variable costs		
Total cost, mills/kWh		
4000 h		21.38
8000 h		15.24

[a] Estimated.

[b] Product credits or disposal costs are unknown.

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APPENDIX A

APPENDIX A. QUESTIONNAIRE DATA ON THE DILUTE SULFURIC ACID FLUE GAS DESULFURIZATION PROCESS

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO Scholz Steam Plant
1.	GENERAL DESCRIPTION		
1.1	Company	Hokuriku Electric Company	Gulf Power Company
1.2	Plant name	Fukui	Sholz Steam Plant
1.3	Preparer's name and mailing address	Jumpei Ando 1-13-27 Kasuga Bunkyo-Ku, Tokyo	Michael D. Giordano 11499 Chester Road Cincinnati, Ohio 45246
1.4	Principal plant products	Electrical power	Electrical power
	Brief description of area durrounding plant site and factors for choice of FGD system	Located near the small town of Mikuni and faces the Japan Sea and Kuzuryu River. Stringent regulations have been applied to the plant.	N.A.
1.5	Plant location	Mikunicho Fukui Prefecture	Chattahoochee (Sneads), Florida
1.6	STATION CAPACITY		
1.6.1	Total boiler generating capacity, MW/number of boilers	350	40/2
1.6.2	Capacity served by FGD system, MW amount of flue gas treated, Nm^3/h	350 N.A.	20 N.A.
	% of boiler flue gas treated by FGD system	100	N.A.
	Number of boilers served	1	2
1.7	TYPE OF FGD SYSTEM	Dilute sulfuric acid/gypsum	Dilute H_2SO_4 (Chiyoda 101)
1.8	Number of scrubber trains in parallel	1	1
1.9	FGD system installed on new or existing boiler	Existing	Existing
1.10	STATUS OF FGD SYSTEM operation or under construction, date started	Operational, June 1976	Shutdown, March 1975

N.A.- Not available.

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
2.	BOILER DATA		
2.1	Boiler identification number	No. 1	Units 1 and 2
2.2	Maximum continuous heat input, MW	930	139
2.3	Max. cont. net generating capacity, MW	350	47.5
2.4	Flue gas flow rate, Nm^3/h	980,000	293,500
	temperature at induced draft fan, °C	141	164
2.5	Boiler manufacturer	N.A.	Babcock and Wilcox
2.5.1	Fuel type	Heavy oil	Coal
2.5.2	Firing configuration	Tangential firing	Pulverized coal fired
2.6	Year placed in service	1974	1953
2.7	Type service	Base load	N.A.
2.8	Stack height, m	295	45.7
2.8.1	Flue gas exit velocity, m/s	37.6	N.A.
2.9	Average boiler operation, h/yr	7290/1976	N.A.
2.10	Average boiler capacity factor	0.63	N.A.
2.11	COAL COMPOSITION	None	
2.11.1	Lower heating value, kJ/kg		26,700-32,800
2.11.2	Sulfur content, %		0.9-5.0
2.11.3	Ash content, %		14.0
2.11.4	Chloride content, %		0.02-0.15
2.11.5	Moisture, %		15.0

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
2.12	OIL COMPOSITION		
2.12.1	Grade/heating value, kJ/kg	Heavy oil 44,000	N.A.
2.12.2	Sulfur content, %	2.5-3.0	
2.12.3	Ash content, %	0.1	
2.12.4	Chloride content, %	0.003	
2.13	PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM		
2.13.1	Type	Electrostatic precipitator	Electrostatic precipitatore
2.13.2	Manufacturer	Mitsubishi Heavy Industries	Buell
2.13.3	Efficiency, % removal	80	99.7
2.13.4	Emission rate, mg/Nm^3	Below 30	N.A.
3.	EMISSION REGULATIONS		
3.1	ATMOSPHERIC EMISSIONS		
3.1.1	SO_2	209 Nm^3/h	0.2 kg/GJ
3.1.2	Particulate	100 mg/Nm^3	0.04 Kg/GJ
3.1.3	NO_x	230 ppm	0.2 Kg/GJ
3.1.4	Other	N.A.	None
3.1.5	Legal basis	National and prefectural standard	Florida state code
3.2	RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES, LEGAL BASIS	National / Prefectural pH 5.8-8.6 / 5.8-8.6 COD (ppm) 160 / 100 SS (ppm) 200 / 120	N.A.

(continued)

APPENDIX A (continued)

	CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4. FGD SYSTEM INFORMATION		
4.1 Process name	Dilute sulfuric acid/gypsum	Thoroughbred 101
4.1.1 Supplier or design company	Chiyoda	Chiyoda Chemical and Construction Co.
4.1.2 WHY WAS THIS SYSTEM CHOSEN?	Process is simple and without scaling problems.	Demonstration
4.1.3 PROCESS DESCRIPTION	Appendix Figures A, B, and C	N.A.
4.2 SO_2 SCRUBBING AGENT		
4.2.1 Name	Dilute sulfuric acid	Dilute H_2SO_4
4.2.2 Chemical composition	H_2SO_4 Fe^{+} (Catalyst)	N.A.
Components, % by weight	H_2SO_4, 1.3-2.5 Fe^{+3} (Catalyst), 0.15-0.25	
4.2.3 Stoichiometric requirement	N.A.	N.A.
4.2.4 Addition rate, kg/h	N.A.	N.A.
4.2.5 Particle size, mm	None	None
4.3 REGENERATION AGENT		N.A.
4.3.1 Name	Limestone	
4.3.2 Composition, %	over 95 $CaCO_3$	
4.3.3 Stoichiometric requirement	1 mole to 1 mole SO_2	
4.3.4 Addition rate, kg/h	5000	
4.3.5 Particle size, mm	90% below 0.074	

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.4	SALABLE PRODUCT		
4.4.1	Name	Gypsum	Gypsum
4.4.2	Chemical composition components, % by weight	$CaSO_4 \cdot 2H_2O$, over 90 Moisture, below 10	CaO, 31.5 CO_2, 0.10 SO_3, 44.75
4.4.3	Amount generated/year	N.A.	N.A.
4.4.4	Sales potential	N.A.	N.A.
4.4.5	BY-PRODUCT RECOVERY PROCESS	None	None
	Name		
	Vendor		
	Process		
4.4a	Intermediate product composition		
4.5	BY-PRODUCT No. 2	None	None
4.6	WASTE STREAMS		N.A.
4.6.1	Type of waste	Wastewater	
	% water	N.A.	
4.6.2	Amount generated in one hour at full load, m^3/h	7-24	
4.6.3	Disposal method	Neutralization and precipitation	
4.6.4	Disposal site and distance from plant, km	0.1	
4.6.5	Potential effects on environment from sludge disposal	N.A.	
4.7	SLUDGE FIXATION PROCESS	None	None

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.8	FGD EQUIPMENT DATA		
4.8.1	FIRST SCRUBBER		
4.8.1.1	Type	Venturi	Venturi
4.8.1.2	L/G[a] ratio, ℓ/Nm^3	N.A.	N.A.
4.8.1.3	Gas velocity through absorber or scrubber, m/s	N.A.	N.A.
4.8.1.4	Absorbent (adsorbent) flow, m^3/h	N.A.	N.A.
4.8.1.5	Gas flow entering scrubber, Nm^3/h	1,005,000	N.A.
4.8.1.6	Gas temperature, °C	141	N.A.
4.8.1.7	Gas composition	N.A.	
	SO_2 in + out, ppm		N.A.
	% removal		N.A.
	Particulate in + out, mg/Nm^3		N.A.
	% removal		99
	NO_x in + out, ppm		N.A.
	CO_2 in + out, ppm		N.A.
	Other in + out		N.A.
4.8.1.8	Material of construction	Titanium and SUS 316L	316L stainless steel
4.8.1.9	Type of lining	N.A.	FRP
4.8.1.10	Adsorbent and sand losses	N.A.	N.A.
4.8.1.11	Number of stages	1	1
4.8.1.12	Packing type and composition	N.A.	N.A.

[a] Liquid-to-gas ratio.

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.8.2	SECOND SCRUBBER		
4.8.2.1	Type	Packed tower	Tower
4.8.2.2	L/G ratio, ℓ/Nm^3	40-60	N.A.
4.8.2.3	Gas velocity through absorber or scrubber, m/s	N.A.	N.A.
4.8.2.4	Absorbent (adsorbent) flow, m^3/h	N.A.	N.A.
4.8.2.5	Gas flow entering scrubber, Nm^3/h	1,070,000	N.A.
4.8.2.6	Gas temperature, °C	58	N.A.
4.8.2.7	Gas composition		
	SO_2 in + out, ppm	1830 + 80	1400 + 210
	% removal	95.6	85
	Particulate in + out, mg/Nm^3	30 + N.A.	N.A.
	% removal	N.A.	N.A.
	NO_x in + out, ppm	230 + N.A.	N.A.
	% removal	N.A.	N.A.
	CO_2, %	12	N.A.
	Other	N.A.	N.A.
4.8.2.8	Material of construction	316L	316L stainless steel
4.8.2.9	Type of lining	N.A.	N.A.
4.8.2.10	Number of stages	1	N.A.
4.8.2.11	Packing type and composition	Tellerette (Plastic)	0.076 m Tellerette

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.8.3	CLEAR WATER TRAY	N.A.	N.A.
4.8.3.1	Type		
4.8.3.2	L/G ratio, ℓ/Nm^3		
4.8.3.3	Source of water		
4.8.4	DEMISTER		
4.8.4.1	Type	Euroform	Chevron
4.8.4.2	Number of passes (stages)	2	2
4.8.4.3	Material of construction	316 L	N.A.
4.8.4.4	Method of cleaning	N.A.	N.A.
4.8.4.5	Flow rate during cleanings, Nm^3/h	N.A.	N.A.
4.8.4.6	Frequency and duration of routine cleaning	N.A.	N.A.
4.8.5	REHEATER		N.A.
4.8.5.1	Type	After burner	
4.8.5.2	Heat load, kW	42,885	
4.8.5.3	Heat transfer surface area, m^2	38.5	
4.8.5.4	Temperature of gas in, °C out, °C	58 90-141	
4.8.5.5	Reheater materials of construction	SS41 lined with plastic refractories	

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.8.6	SCRUBBER TRAIN PRESSURE DROP, mbar		N.A.
4.8.6.1	First scrubber	N.A.	
4.8.6.2	Second scrubber	N.A.	
4.8.6.3	Clear water tray	N.A.	
4.8.6.4	Demister	N.A.	
4.8.6.5	Reheater	N.A.	
4.8.6.6	Ductwork	N.A.	
4.8.6.7	Total FGD system	67	
4.8.6.8	I.D. fan	83	
4.9	SYSTEM MAKEUP WATER ADDED, m^3/h	87.5	N.A.
4.9.1	Water added per mole of SO_2 removed, m^3/kg mol		
4.9.2	Source of makeup water	Industrial water	
4.9.3	Where is water added	Absorber	
4.10	BYPASS SYSTEM		N.A.
4.10.1	Can flue gas be bypassed?	Yes	
4.10.2	Height of gas discharged when bypassed, m	N.A.	
4.11	SLURRY DATA, pH, % SOLIDS BY WEIGHT	N.A.	N.A.
4.11.1	Fresh slurry to scrubber		
4.11.2	Recirculating slurry		
4.11.3	Waste slurry		

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.12	SPENT SLURRY SYSTEM		N.A.
4.12.1	Clarifiers	N.A.	
4.12.1.1	Number		
4.12.1.2	Diameter, m		
4.12.2	Solid separation		
4.12.2.1	Type	Centrifuge (6 basket type units)	
4.12.2.2	Cloth area, m^2	3.6 (per unit)	
4.12.2.3	Capacity (wet cake), kg/h	2200 unit	
4.13	SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA, m^2	N.A.	N.A.
4.14	PERSONNEL, man-hours/year		N.A.
4.14.1	Operating	N.A.	
4.14.1.1	Specialists	20,800	
4.14.1.2	Unskilled	N.A.	
4.14.2	Maintenance and repair	3300	
4.15	ENVIRONMENTAL LOAD		N.A.
4.15.1	Wastewater treatment process	Neutralization	
4.15.2	Concentrations	N.A.	
4.15.3	Appearance of flue gas discharge Any mist problems?	No plume	

(continued)

APPENDIX A (continued)

	CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
4.16 FGD SYSTEM OPERATION		N.A.
4.16.1 % of boiler load FGD can operate	N.A.	
4.16.2 Lag time	None	
5. ACTUAL COSTS FOR TOTAL FGD INSTALLATION, year	N.A.	1975
5.1 CAPITAL COSTS, $	N.A.	N.A.
5.1.1 Scrubber		N.A.
5.1.2 Absorbent/regeneration system		N.A.
5.1.3 Sludge disposal system		N.A.
5.1.4 Site improvements		N.A.
5.1.5 Land, roads, tracks, substation		N.A.
5.1.6 Engineering costs		N.A.
5.1.7 Contractor's fee		N.A.
5.1.8 Interest during construction		N.A.
Construction period, mo		
5.1.9 License fees		N.A.
5.1.10 Other		N.A.
5.1.11 Total, $		5,408,011 (as of Feb. 1975)

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
5.2	ANNUAL COSTS		
5.2.1	Interest	N.A.	N.A.
5.2.2	Depreciation	N.A.	N.A.
5.2.3	Insurance and taxes	N.A.	N.A.
5.2.4	Total fixed costs	N.A.	N.A.
5.2.5	Labor and overhead Average man hour cost, cost/year	N.A.	350,067 (to operate 3 systems) 3 men and supervisor 4 shifts/day
5.2.6	Raw material breakdown	Limestone / Catalyst	Lime / Catalyst
	Unit cost	26/(¥ 7900/Mg) / 0.25/kg (¥ 75/kg)	23.55/Mg / 43,236.91
	Annual cost	666,667(¥0.2 billion) / 103,333(¥31 million)	0.02/kg / 26,472.56
5.2.7	Utilities, unit cost, annual costs	Unit / Annual	Consumption / Annual
	Electricity	A 1.63 million (¥ 489 million)	3,656,000 kWh / 100,000
	Water	80 thousand (¥ 24 million)	87,228 m^3 / 60 (pumping)
	Steam	167 thousand (¥ 50 million)	N.A. / N.A.
	Fuel	1.31 million (¥ 392 million)	628.5 m^3 / N.A.
5.2.8	Maintenance cost/year	N.A.	558,692 (1976)
5.2.9	Other costs, list	N.A.	N.A.
5.2.10	Total variable cost/year	N.A.	N.A.
5.2.11	Total annual cost	N.A.	N.A.
5.3	WASTE DISPOSAL COST, $	N.A.	N.A.
	Unit cost		
	Annual cost		
5.4	BY-PRODUCT CREDIT, $	N.A.	N.A.
5.4.1	By-product 1		
5.4.2	By-product 2		

¥ = Yen

(continued)

APPENDIX A (continued)

		CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
5.5	NET ANNUAL COST, kWh/mills	N.A.	N.A.
5.5.1	Cost last year		
5.5.2	Cost at maximum continuous rating		
5.5.3	Cost without FGD		
6.	ENERGY REQUIREMENTS, kW		N.A.
	Pumps	5300	
	Fan	5500	
	Reheat	42885	
	Reductant chemicals		
	Other	1500	
	Total	12,300	
	Per Mg of SO_2 removed, kWh/tons/SO_2 or per kW of electricity	0.035	
7.	PERFORMANCE HISTORY: OPERATING PROBLEMS AND SOLUTIONS		
7.1	Scrubber system	N.A.	N.A.
7.2	Demister	N.A.	N.A.
7.3	Reheater	N.A.	A) Burner controls B) Scanner failure, refractory failure
7.4	Fan	N.A.	Corrosion required frequent balancing

(continued)

APPENDIX A (continued)

	CHIYODA Fukui	CHIYODA CHEMICAL AND CONSTRUCTION CO. Scholz Steam Plant
7.5 Sludge system	N.A.	Centrifuge wear was excessive requiring frequent rebuilding
7.6 Regeneration system	A part of rubber lining was broken at the start up. (crystallizer lining)	N.A.
7.7 By-product system	N.A.	N.A.
7.8 Other	N.A.	N.A.
7.9 Availability, %	100	81 (1976)

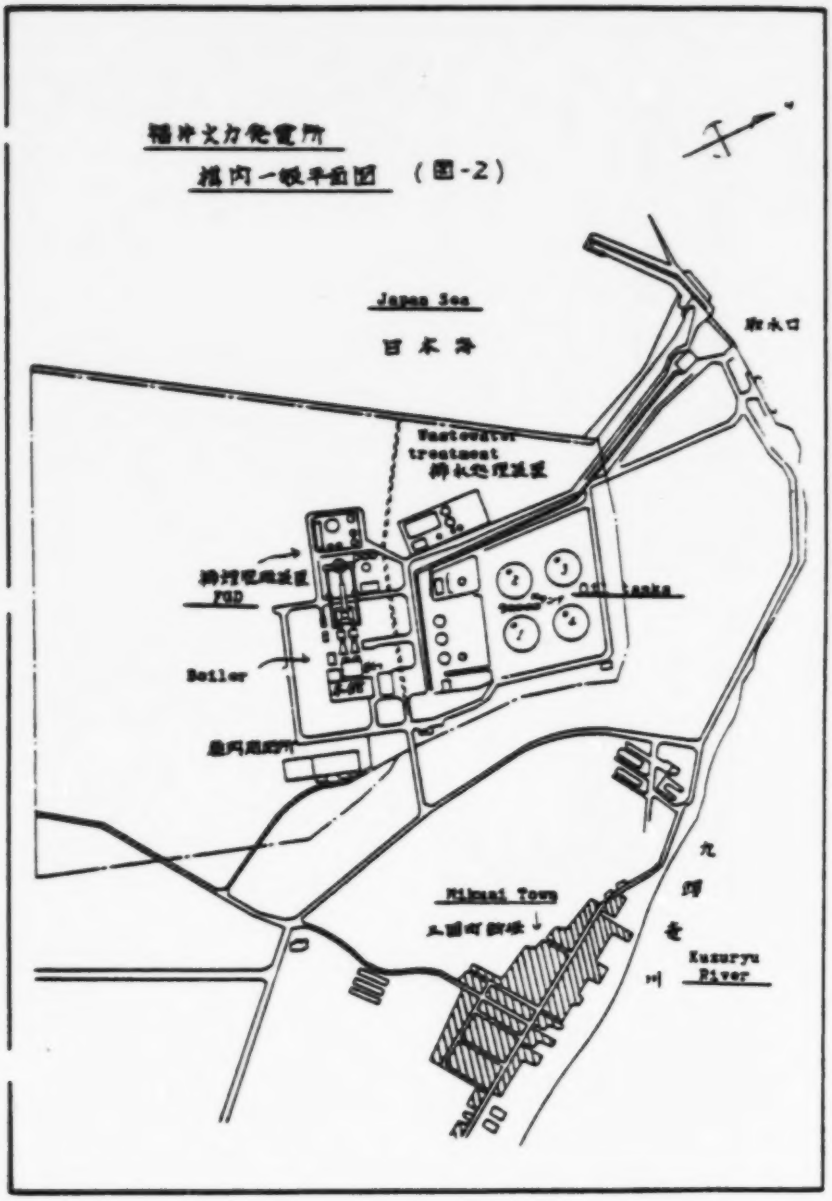

Figure A. Location of Fukui Plant.

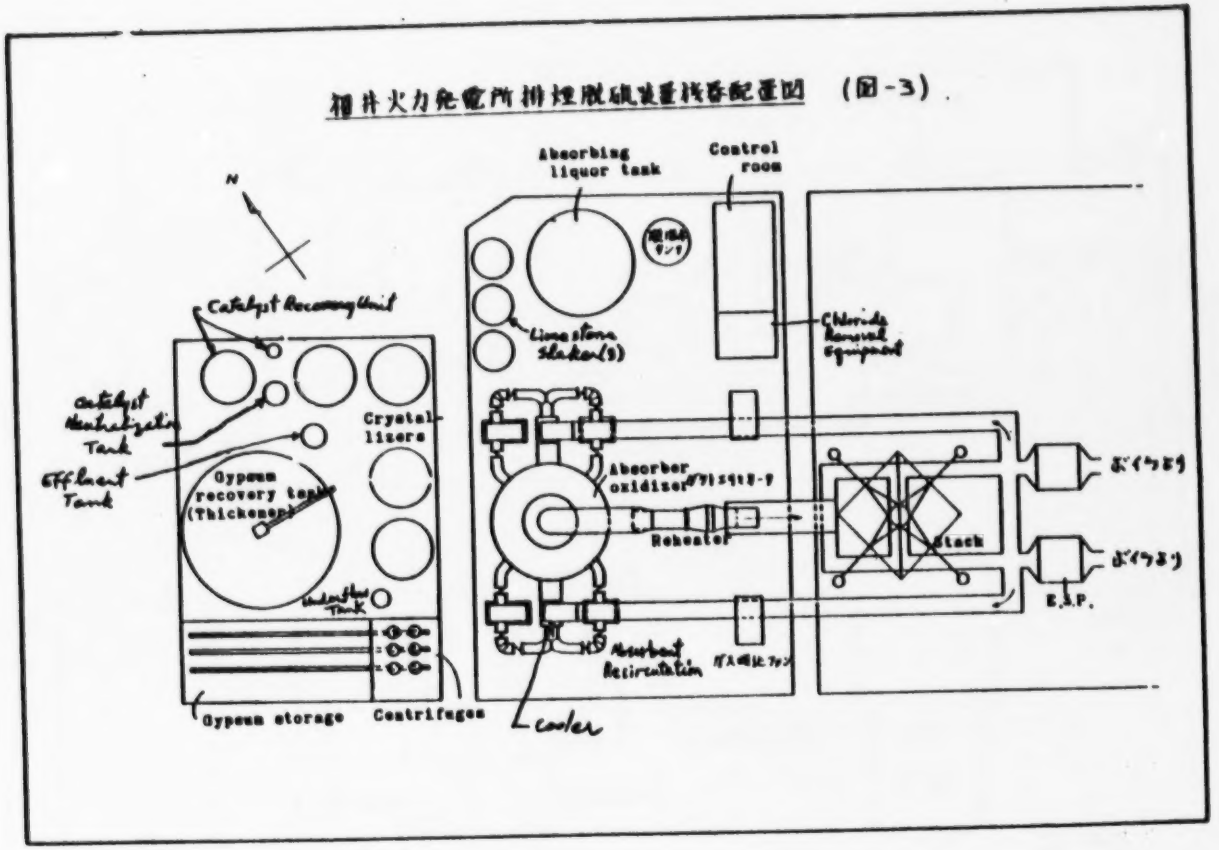

Figure B. Layout of Fukui Plant.

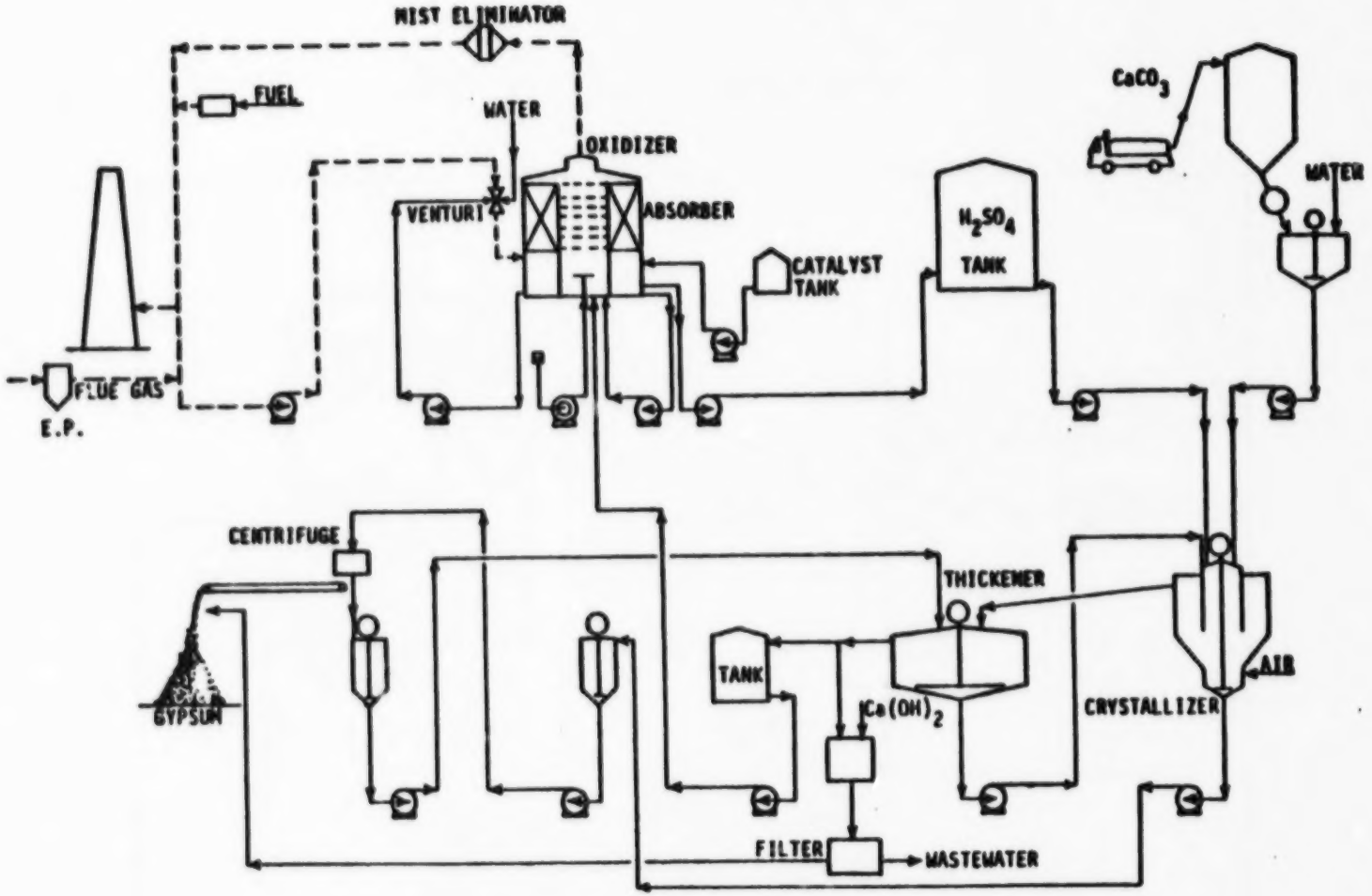

Figure C. Flowsheet of Chiyoda process (Fukui plant, Hokuriku Electric).

APPENDIX B

APPENDIX B

Availability Factor Computation

1. Divide boiler capacity by the number of modules and obtain MW/module = x

2. Multiply boiler capacity by number of hours during selected period (MW) = a

3. Add all down times due to module trouble for all modules during selected period = b

4. Add all down times due to boiler trouble or reduction in electricity demand for all modules during period = c

5. Availability factor = $\frac{[a - x\ (b + c)]\ 100}{a - x\ c}$ = %

APPENDIX C

APPENDIX C. CONVERSION FACTORS USED IN THIS STUDY

Multiply	By	To Obtain
ft	x 0.30480	m
ft^3	x 28.317	liter
Btu/lb	x 0.55554	kcal/kg
	x 2.32593	kJ/kg
Btu/h	x $0.29300 \cdot 10^{-3}$	kW
acfm	x 1.6992	m^3/h
$lb/10^6$ Btu	x 1.80005	mg/kcal
	x 0.42993	mg/kJ
gal/min	x 3.78541	liter/min
	x 0.22712	m^3/h
gal/1000 ft^3	x 0.13368	liter/m^3
ft^3/min	x 1.6992	m^3/h
kcal	x 4.1868	kJ
kcal	x $1.163 \cdot 10^{-3}$	kWh
scfm	x 1.60776	Nm^3/h
gr/ft^3	x 2.288	g/m^3
gr/scfm	x 2.4182	g/Nm^3
in. H_2O	x 0.2488	kPa
in. H_2O	x 2.54	mbar
gr	x 0.0648	g
ton (short)	x 1.9072	metric ton

1 MW corresponds to 3200 to 3500 m^3/h flue gas (coal)

1 scfm = 28.317 l (60°F / 14.7 psia)
(15.5°C / 760.28 torr)

26.796 l (0°C/760 torr) = 0.026796 Nm^3

6 SO_2 = 2.927 g/liter

MW = electric power generated unless other wise specified